

Ocean Color Radiometry

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Sponsors & Collaborators

- National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Center for Satellite Applications and Research (NOAA/NESDIS/STAR)
- National Aeronautics and Space Administration, Science Mission Directorate, Earth Science Division (NASA/SMD/ESD)
- University of Miami (UM)
- Moss Landing Marine Laboratories (MLML), San Jose State University Research Foundation (MLML/SJSURF)
- San Diego State University (SDSU)
- Utah State University, Space Dynamics Laboratory (USU/SDL)
- Institute for Environment and Sustainability, Joint Research Centre (JRC), Italy

Outline

- Why Ocean Color
- Description of the Problem (and Solution)
- Vicarious Calibration of Satellite Sensors – In Water Radiometry
- Validation of Ocean Color Products – In Air Radiometry
- Summary

Objective

To provide measurement support for ocean color remote sensing studies of the world's oceans, leading to a better understanding of their ecology and biogeochemistry and, in particular, their response to the increasing concentration of atmospheric CO₂.

Chlorophyll Concentrations and Land Color, SeaWiFS

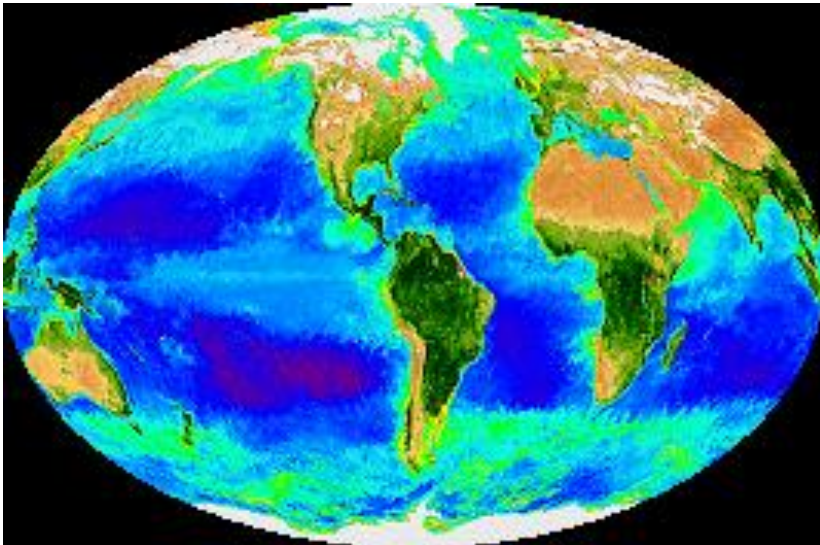


Image Credit: SeaWiFS instrument aboard the OrbView-2 spacecraft; <http://oceancolor.gsfc.nasa.gov/SeaWiFS/HTML/SeaWiFS.BiosphereAnimation.html>

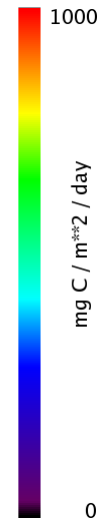
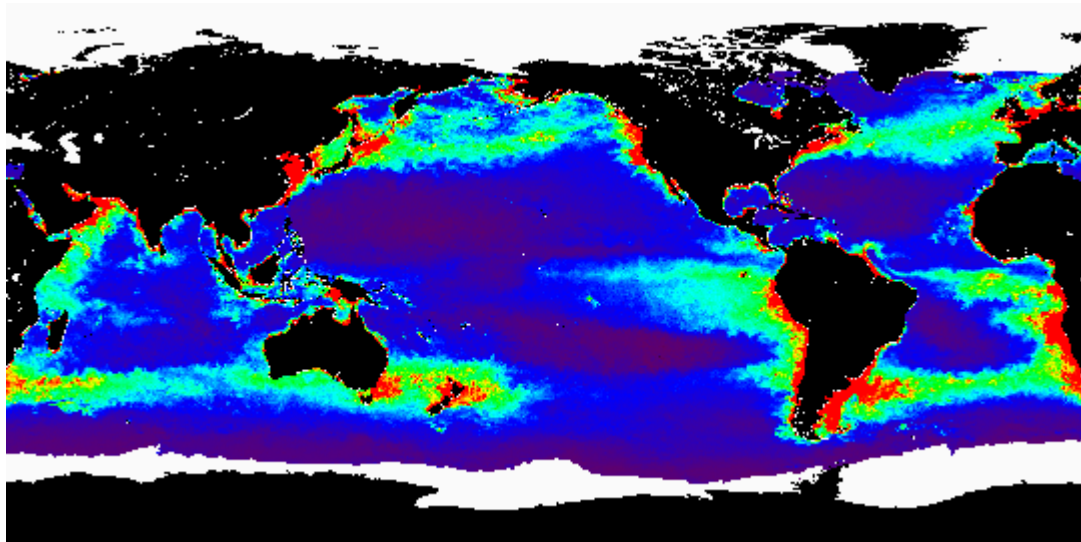
In a nutshell:

Ocean Color Satellite Sensors provide global information on the biosphere and biogeochemistry of the world's oceans. Chlorophyll indicates photosynthesizing organisms are present, having converted dissolved CO₂ to organic matter, depending on sunlight (insolation), temperature, nutrients, rainfall, stratification, and other factors. Chlorophyll absorbs in the blue, changing the color of the ocean. The **spectral radiance scattered from the water** is indicative of the concentrations of chlorophyll and other constituents such as colored dissolved organic material, supporting research into the **ocean carbon cycle**.

Oceans, Greenhouse Gases, and Climate

Example research questions surrounding the oceans as a sink of CO₂:

- CO₂ flux rate into the oceans – what is it
- Physical models of the influencing parameters for this diffusion - dissolving process
- How much stays there, and how – the carbon available for plant growth (Net Primary Productivity)
- Phytoplankton, the oceanic biological pump, and the marine ecosystem
- Can the oceanic flux of CO₂ be modeled into the future, given future changes in ocean circulation patterns and biology



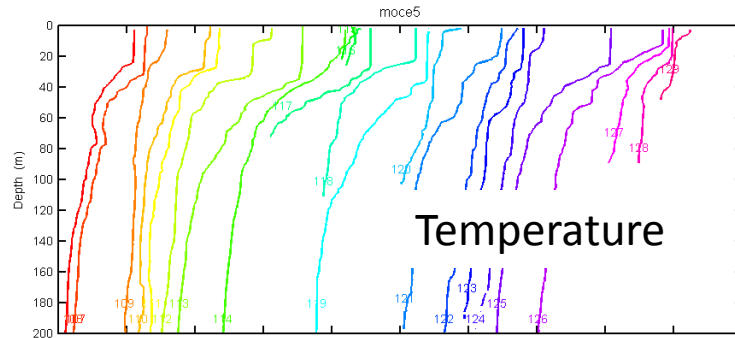
Monthly net primary productivity, September 2002,
MODIS

<http://www.science.oregonstate.edu/ocean.productivity/>

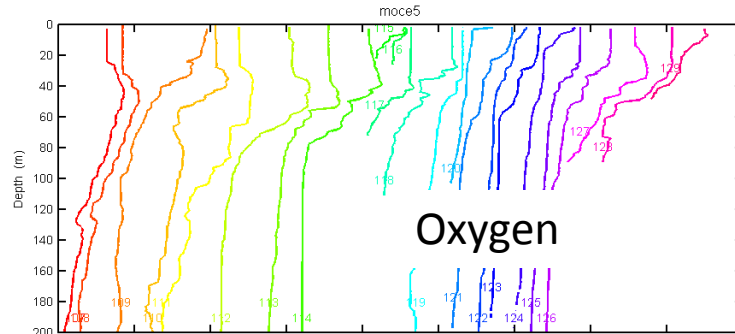
Ocean Color, Greenhouse Gases, and Climate

Example of physical profiles of upper surface layers – each line is one profile taken daily during a cruise

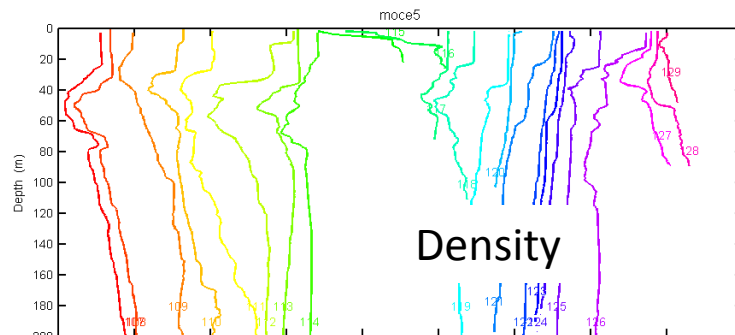
http://data.moby.mlml.calstate.edu/timeseries/ctd/moce5/all_ctd.htm



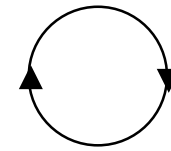
Temperature (°C), Each Tick is 20 °C



Oxygen (mM), Each Tick is 5 mM

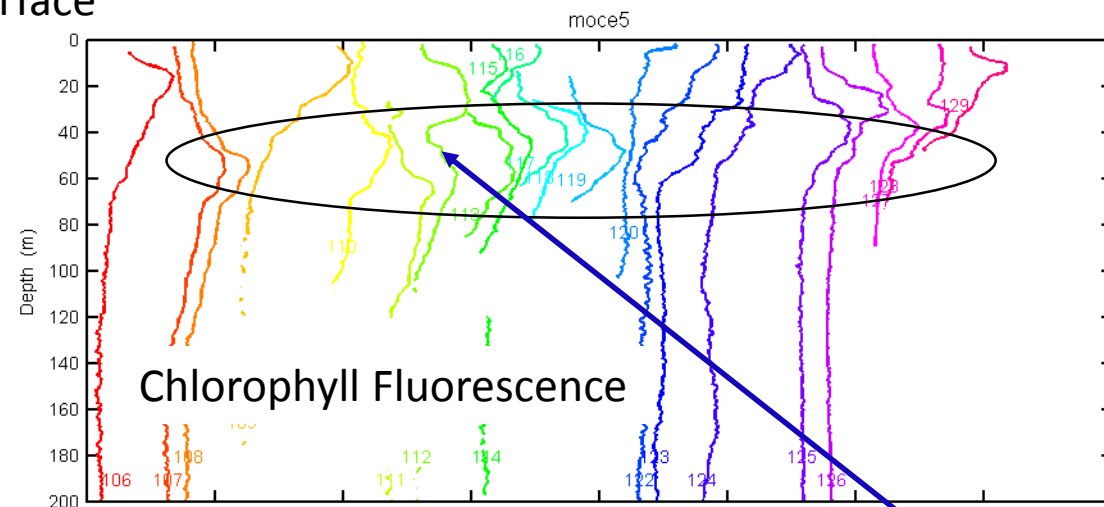


Salinity (PSU), Each Tick is 1 PSU



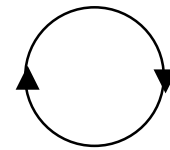
atmosphere – ocean
interactions

Surface



MLML Fluorometer 680 nm (rfu) -, Each Tick is 5 rfu

200 m depth

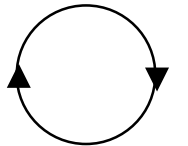


deep ocean circulation
(1000 years)

Biota affect the
optical depth and
temperature
structure

Sunlight

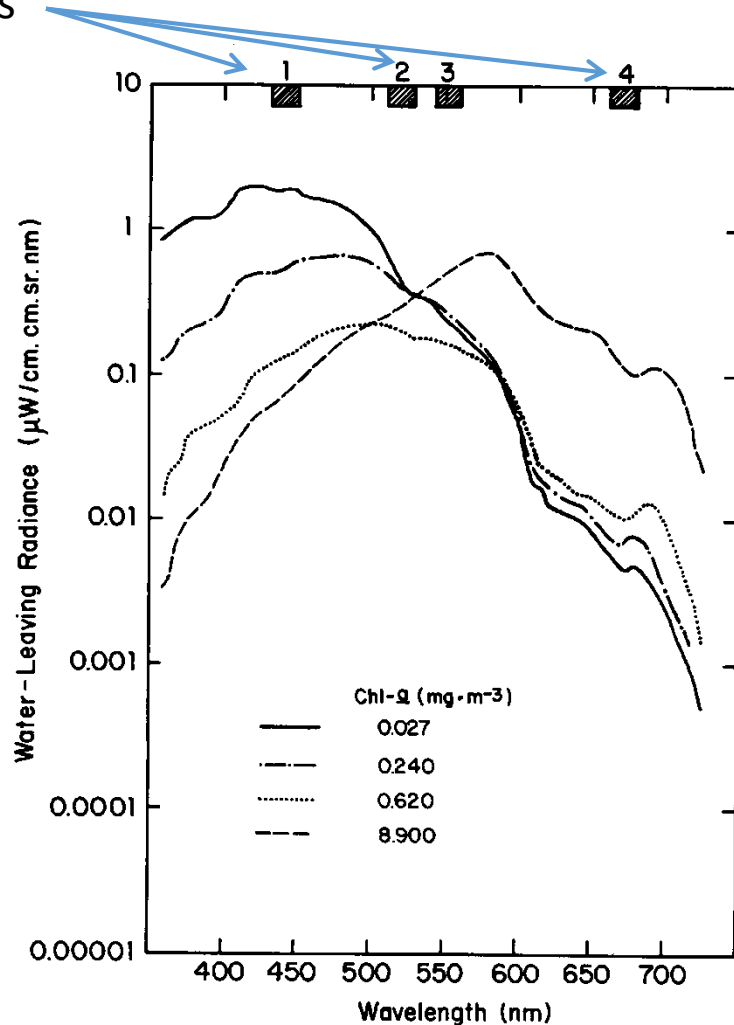
upper ocean
circulation



Nutrients

Ocean Color and Optical Properties

CZCS Bands



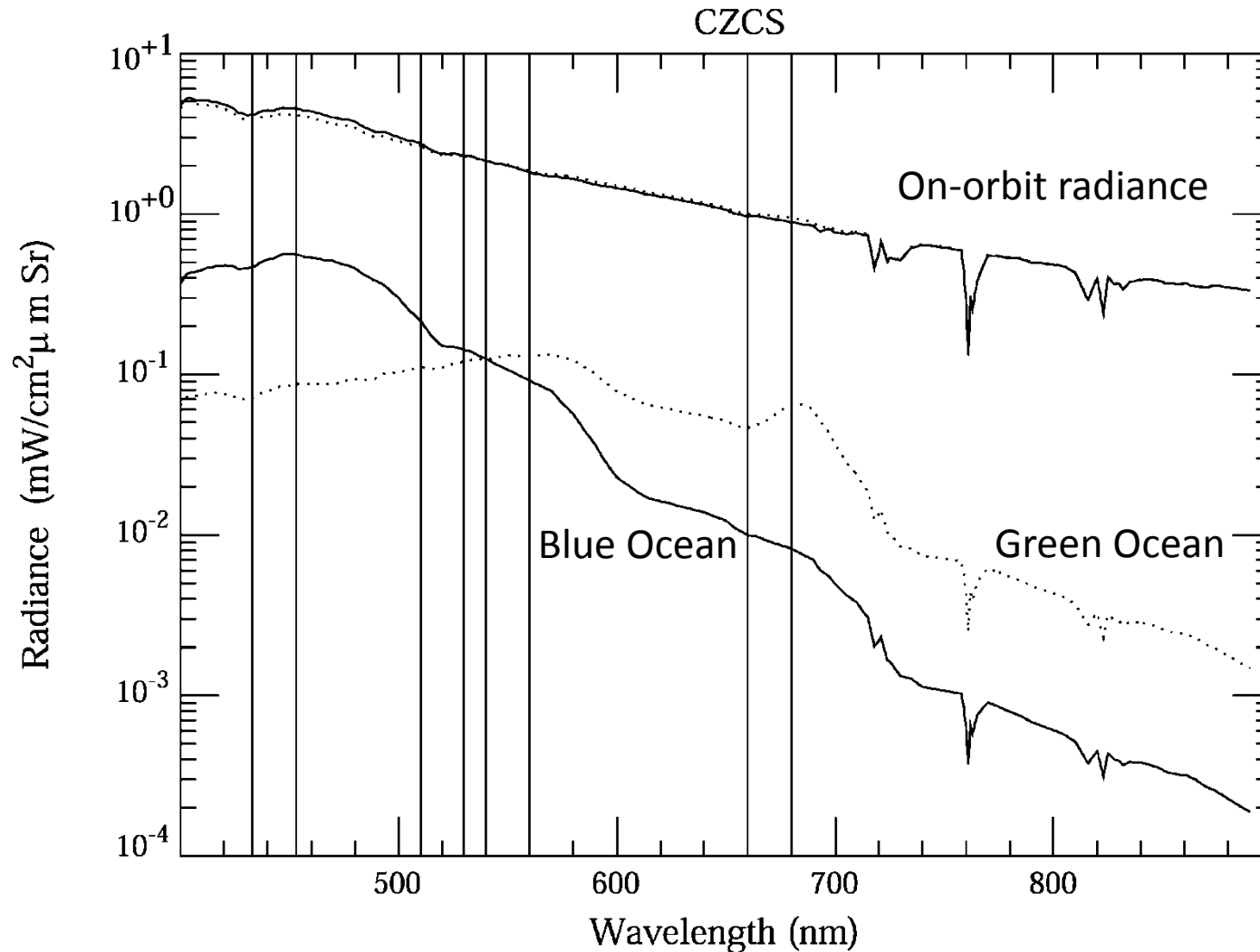
The water-leaving radiance, $L_w(\lambda)$, or the remote sensing reflectance, $R_{RS}(\lambda)$, are related to the optical properties of the water:

$a(\lambda)$ = absorption coefficient;
 $b_b(\lambda)$ = backscatter coefficient.

This is the theoretical basis of bio-optical algorithms that relate $L_w(\lambda)$ to chlorophyll concentrations, typically as a function of band ratios – **note the region around 550nm is less sensitive to Chlorophyll.**

Figure from Gordon *et al.*, 1985, in "Satellite Oceanic Remote Sensing," by way of K. Voss, UM

Ocean Color from Space is Difficult



- The atmosphere and other sources (sun glint, foam) contribute over 90% of the on-orbit radiance
- Uncertainty requirement on Lwn is 5% at 443nm and clear, open oceans
- This 0.5% requirement for satellite calibration & characterization cannot be met pre-flight
- A vicarious calibration method for the ocean-atmosphere system is used

In Water Ocean Color Vicarious Calibration

Marine Optical BuoY (MOBY)

UM

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MLML, SJSURF

Mark Yarbrough, PI
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Stephanie Flora
Terrence Houlihan
Darryl Peters
Sandy Yarbrough

NOAA

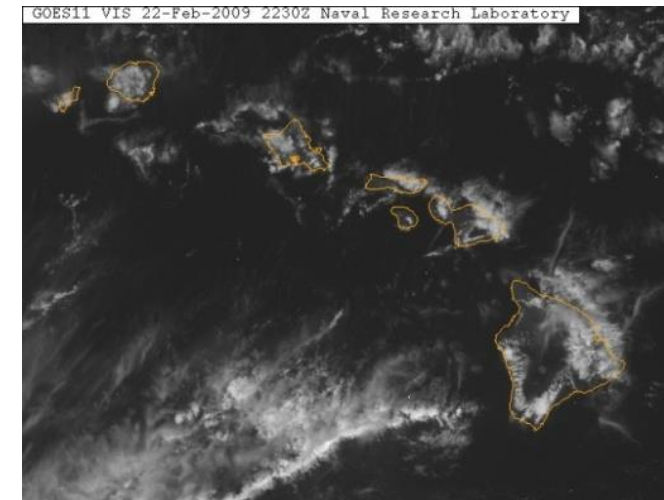
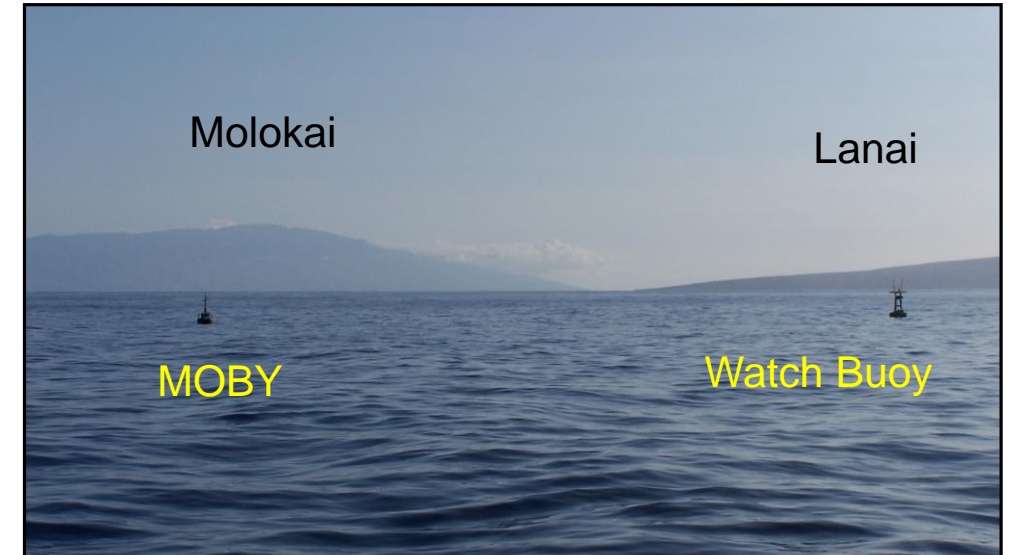
Yong Sung Kim
Veronica Lance

SDSU

James Mueller

USU/SDL

Dennis Clark
Al Parr



Sensor Radiance $L_t(\lambda)$ & Water Leaving Spectral Radiance $L_w(\lambda)$

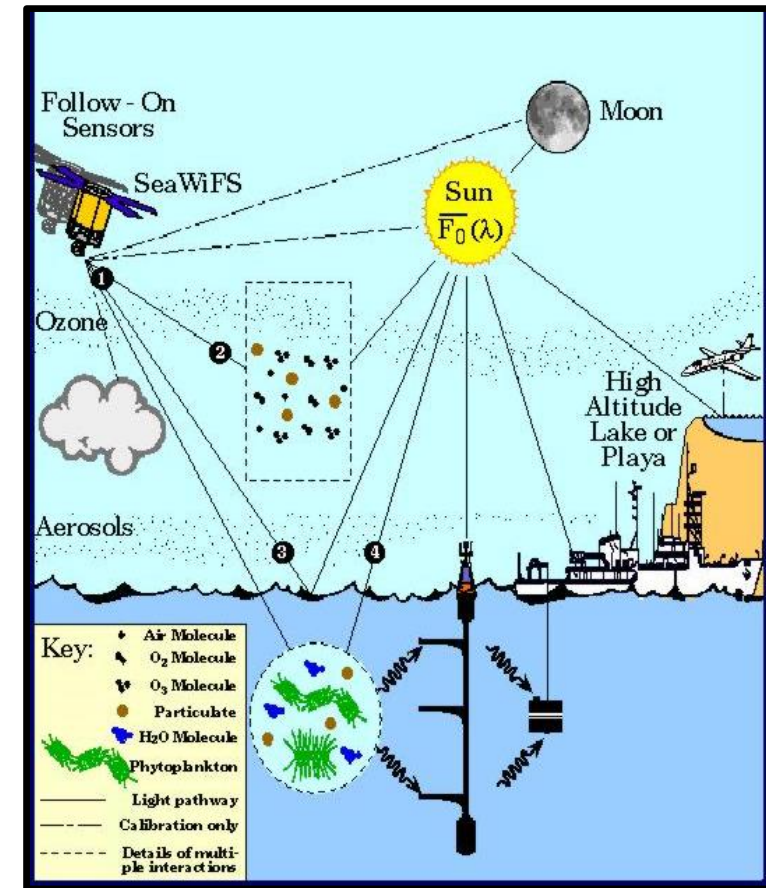
The satellite sensor measures $L_t(\lambda)$ & we want $L_w(\lambda)$

$$L_t(\lambda) = \left[L_r(\lambda) + L_a(\lambda) + t_{d_v}(\lambda)(L_f(\lambda) + L_w(\lambda)) \right] t_{g_v}(\lambda) t_{g_s}(\lambda) f_p(\lambda)$$

The Rayleigh and foam radiances are known from atmospheric pressure and wind models; the diffuse and gaseous transmittances are known from ancillary data; the polarization correction factor is sensor-dependent, leaving $L_a(\lambda)$ and $L_w(\lambda)$ as unknowns. $L_a(\lambda)$ is estimated from the satellite NIR bands; the assumption is $L_w(\lambda=\text{NIR}) \approx 0$. Then we can solve for the only unknown, $L_w(\lambda)$, resulting in a satellite retrieval for this quantity.

$$L_{wn}(\lambda) = \frac{L_w(\lambda)}{\mu_s f_s t_{d_s} f_p f_\lambda}$$

The product algorithms (e.g., for chl a) depend on normalized water-leaving spectral radiance, $L_{wn}(\lambda)$: Sun overhead, 1 AU, with atmosphere correction, and consideration of the ocean BRDF and satellite out-of-band effects.

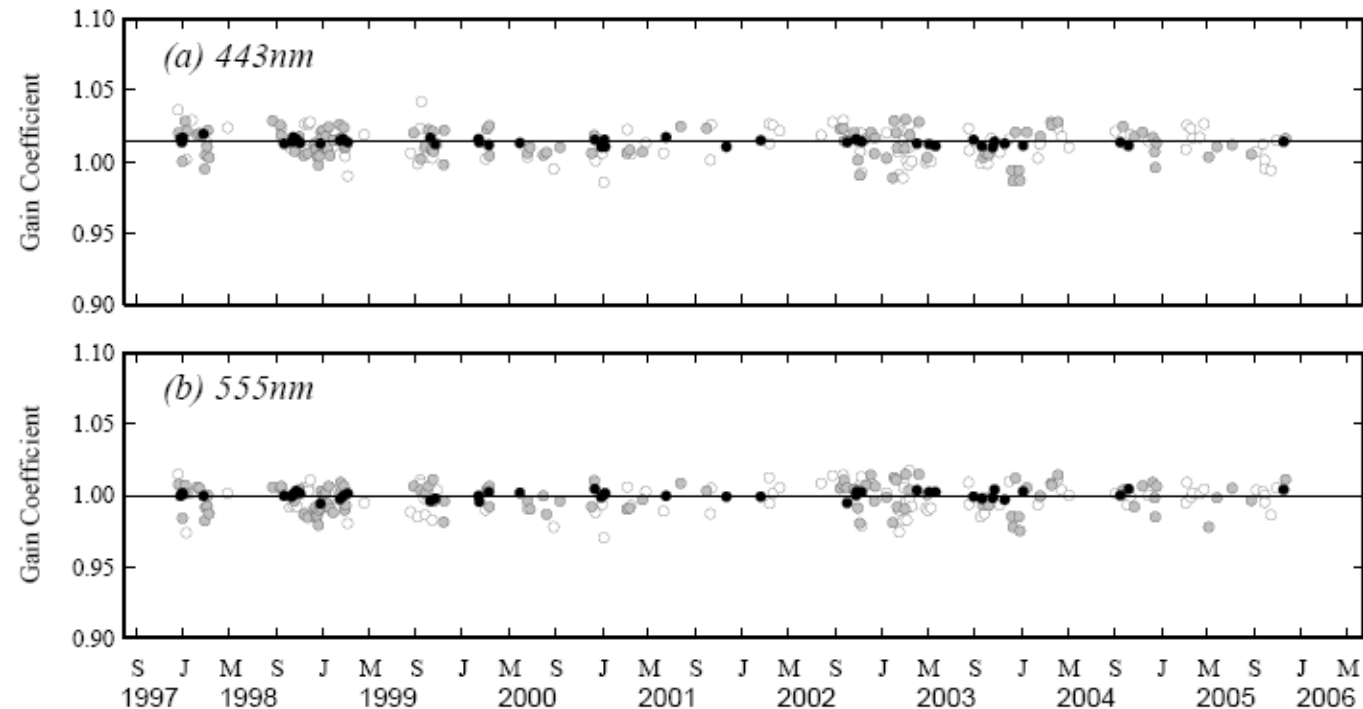


In Situ Vicarious Calibration from Satellite – MOBY Matchups

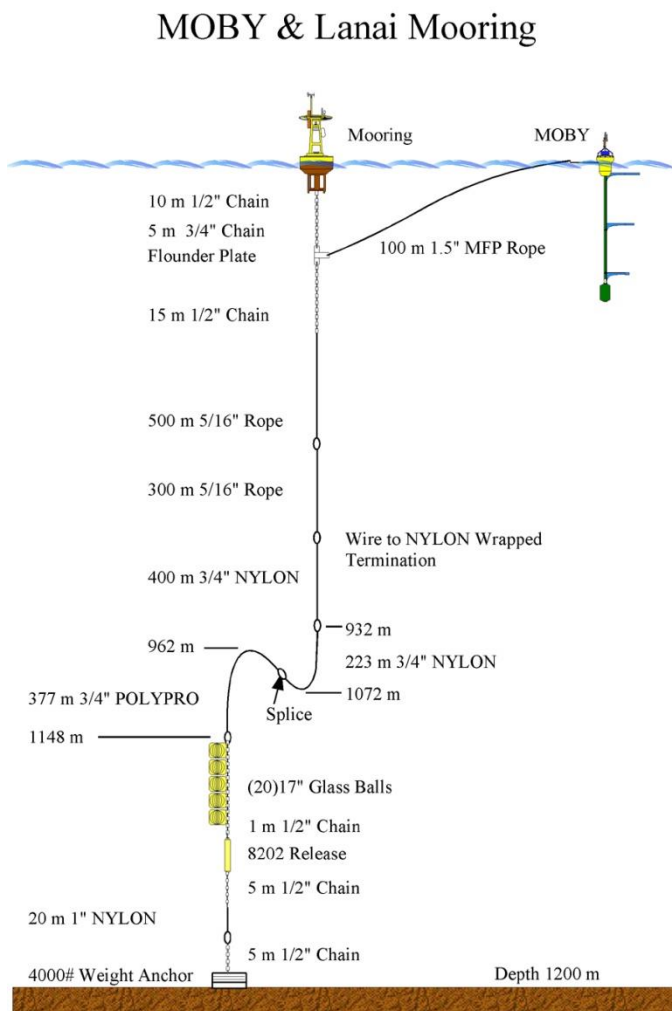
Global Observations: $L_t(\lambda) \rightarrow L_a(\lambda) \rightarrow L_w(\lambda) \rightarrow L_{wn}(\lambda) \rightarrow$ Bio-optical products

Vicarious Calibration: $L_w^r(\lambda) \rightarrow L_{wn}^r(\lambda) \rightarrow L_t^r(\lambda) \rightarrow \frac{L_t^r(\lambda)}{L_t(\lambda)} =$ Gain correction factors

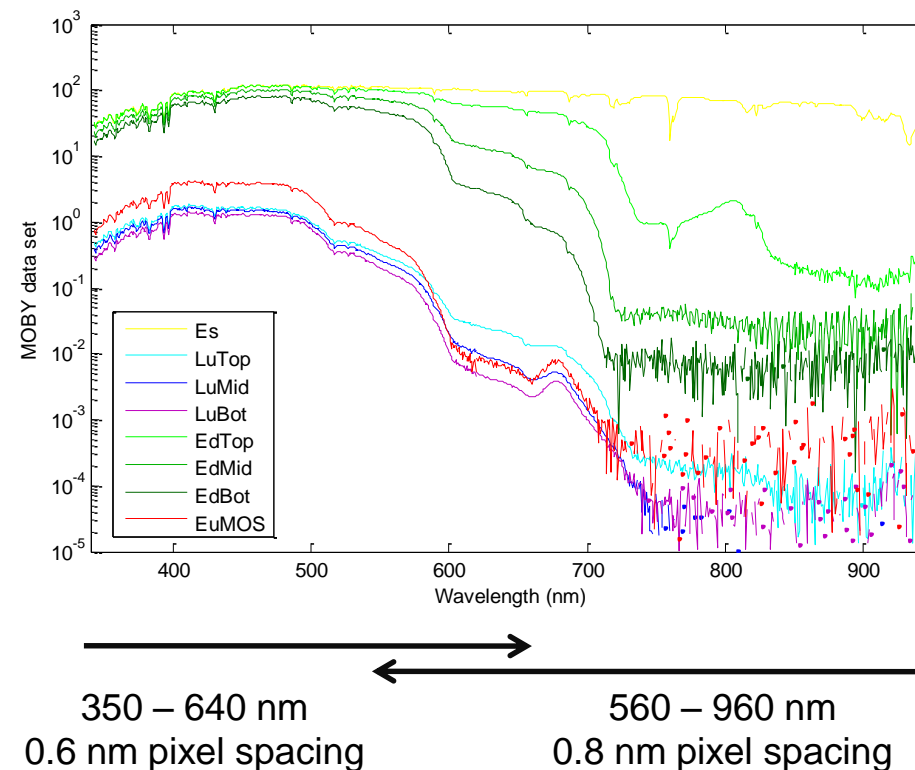
SeaWiFS gain correction factors for
the MOBY matchup series from 1997
to 2006 at 443nm and 555nm



MOBY Measurements



Downwelling irradiance and upwelling radiance



Three daily files (22 h, 23 h, 00 h)

5 to 6 month deployments

Two systems interchanged in ~ 3 day cruises

MOBY Data Products

Fundamental Products

$E_s(\lambda)$, Down-welling spectral irradiance at the surface;
 $E_d(\lambda)$, Down-welling spectral irradiance at 1, 5, & 9m;
 $L_u(\lambda)$, up-welling spectral radiance at 1, 5, 9, and 12 m;
 Host of housekeeping and ancillary data

Intermediate Products

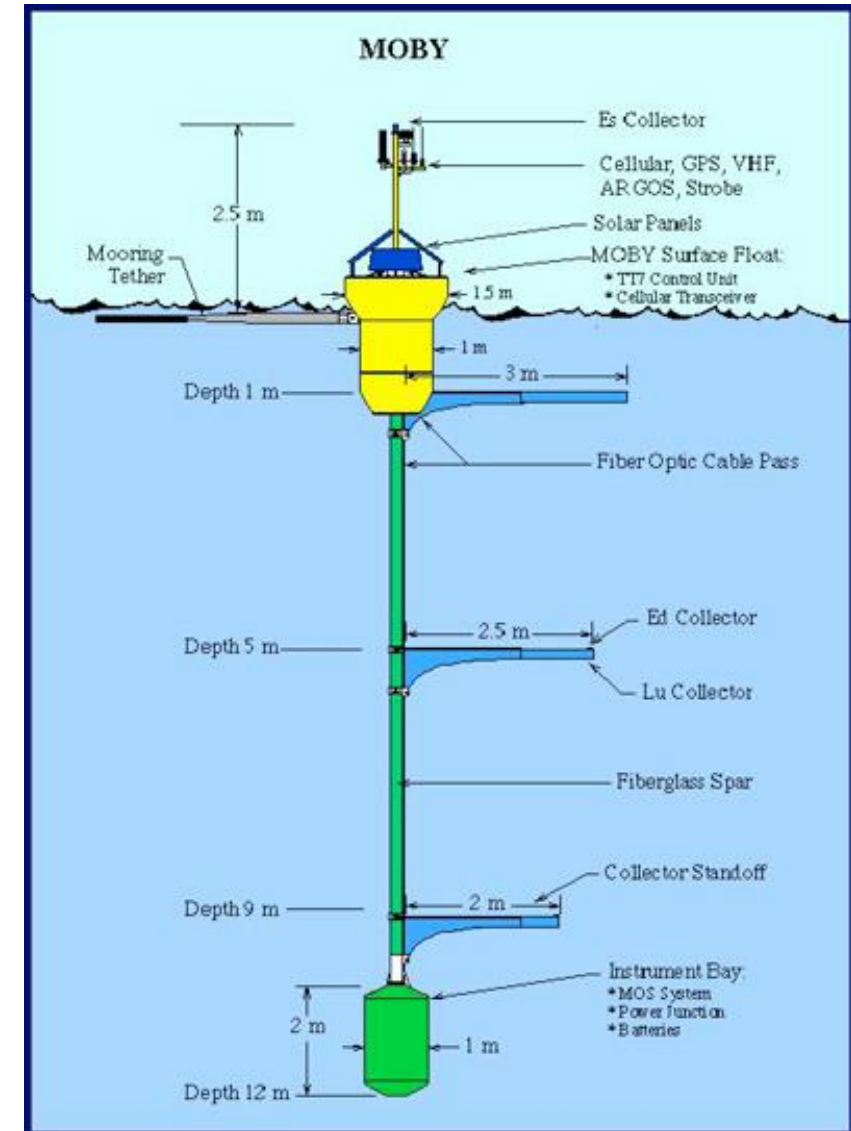
$K_{Lu}(\lambda)$, diffuse attenuation coefficient for $L_u(\lambda)$, using different depth pairs of $L_u(\lambda)$

Final Products

Satellite band averaged values of $E_s(\lambda)$, $L_w(\lambda)$, and $L_{wn}(\lambda)$

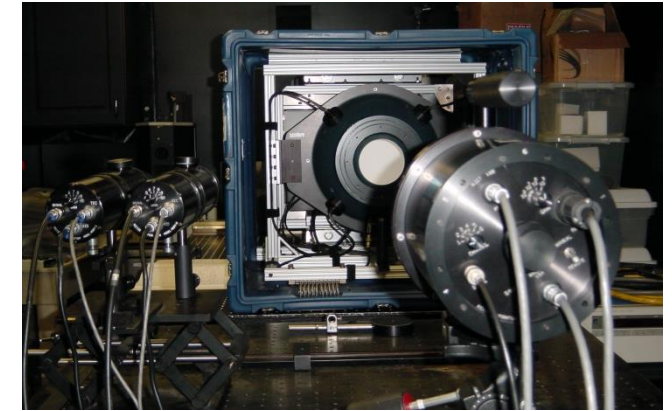
<http://moby.mlml.calstate.edu/>

Time Series: 1997 - Present

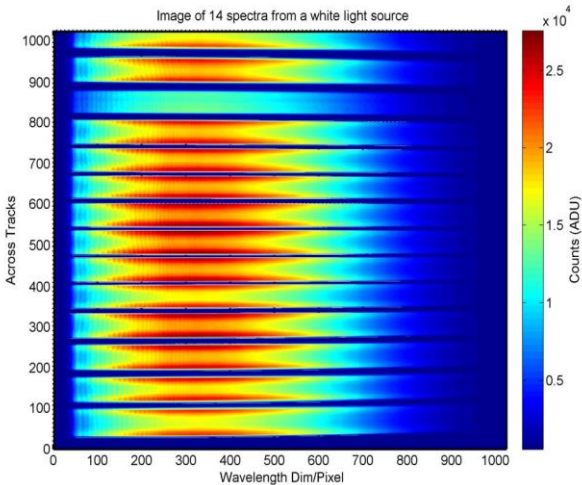


MOBY – NIST Current Projects

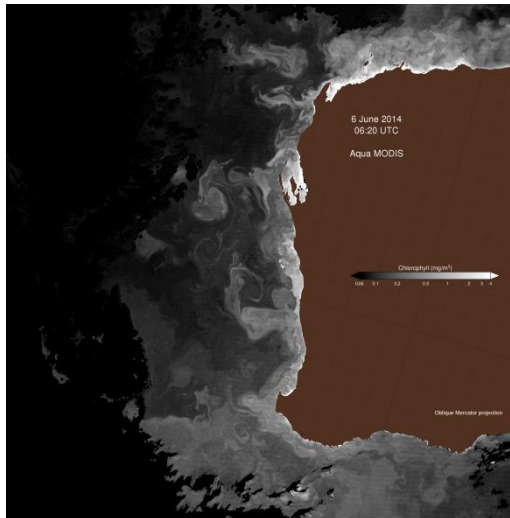
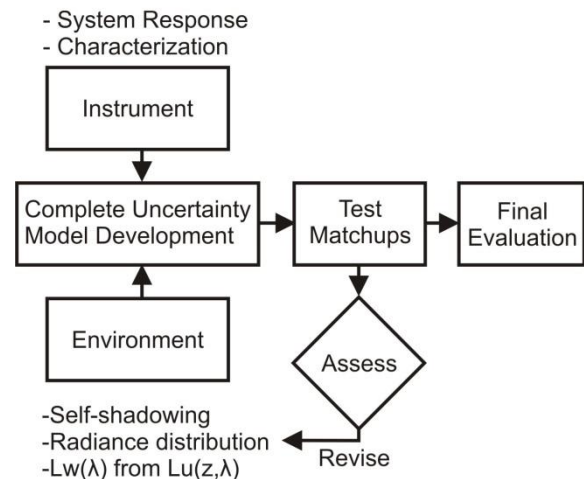
NOAA – MOBY Operations; ongoing and recurring activities to support radiometric characterization and calibration of MOBY optical systems (20 years and counting)



NOAA – MOBY Refresh; multiyear activity to replace the aging systems, including new spectrographs that will measure all channels simultaneously



NASA – MOBY Uncertainties; 4 year project to identify sources of bias, develop and apply correction algorithms for these effects, and evaluate and document uncertainties (ends FY2015).



NASA – MOBY-NET; Proposed effort to duplicate MOBY for a Southern Ocean site; NIST’s responsibility would be maintaining the radiometric scale during routine shipment of the optical system to the MOBY Calibration Facility in Honolulu. Decision August 2014.

MOBY Refresh

Main Features

Preserves all current MOBY capabilities

Redesigned optical systems, to 350nm

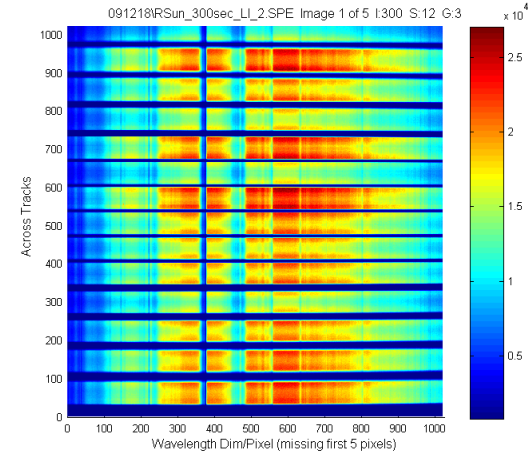
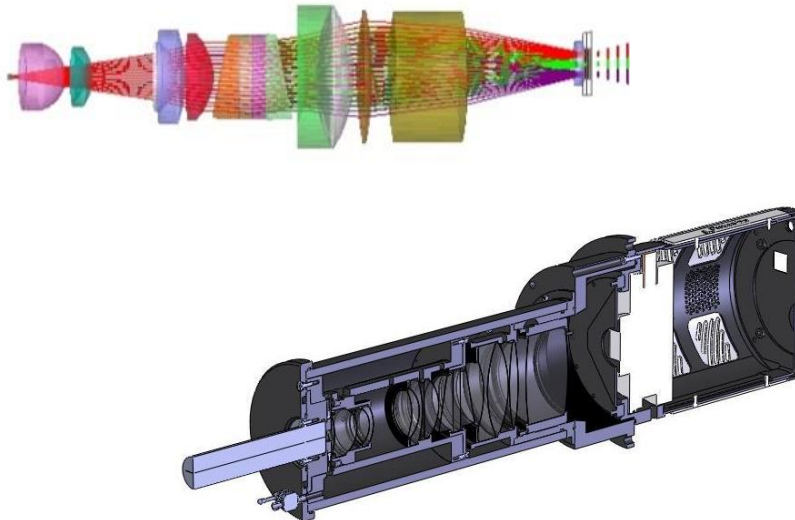
Simultaneous measurements – radiometry and ancillary data

New control system

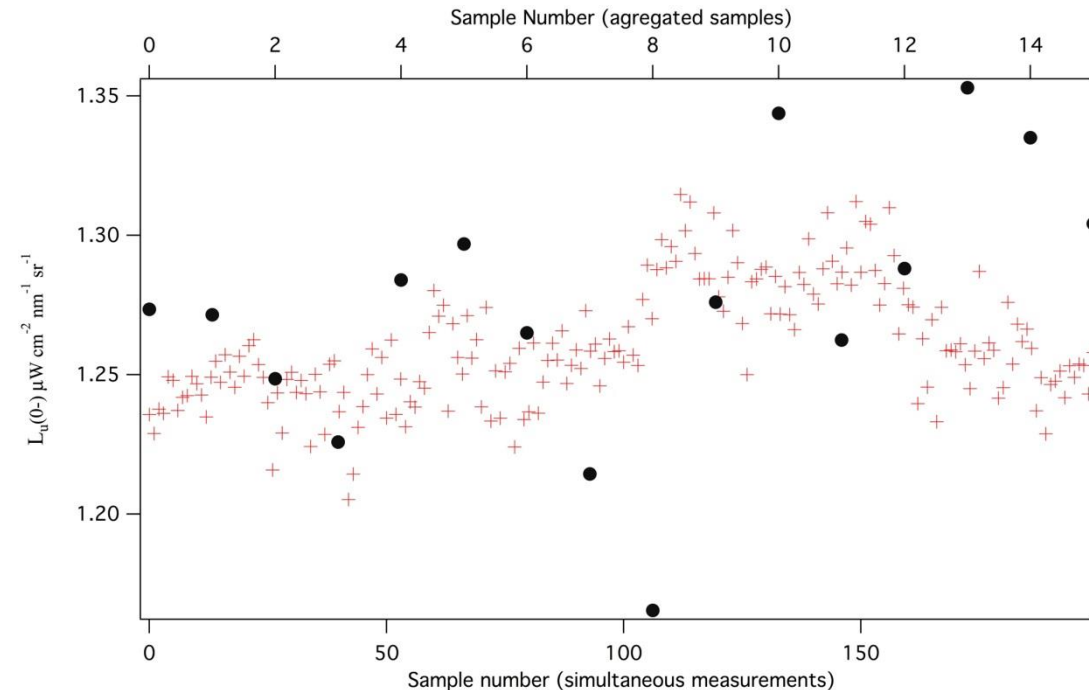
UV bio-fouling mitigation

Improvements to in situ checks of radiometric responsivities

Side-by-side tests with MOBY



Simultaneous vs sequential acquisition will reduce measurement uncertainties and so decrease the number of matchup pairs required for Vic/Cal



Uncertainty in MOBY Products

Instrument

Characterization

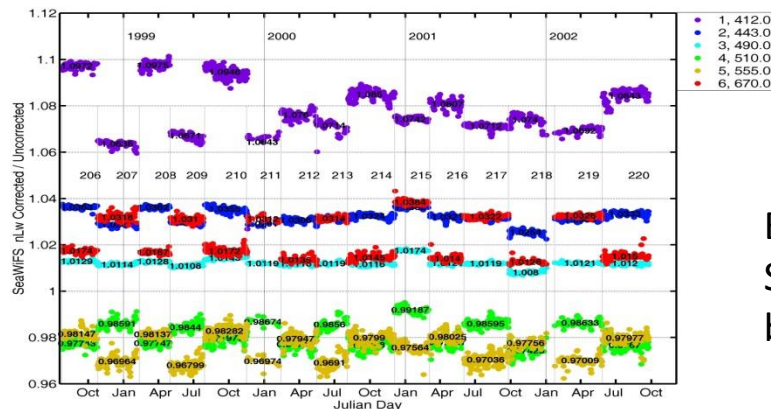
SNR, integration time, short term repeatability, wavelength calibration stability, correction for ambient temperature, correction for stray light, correction for immersion factor, cosine response

Calibration data sets

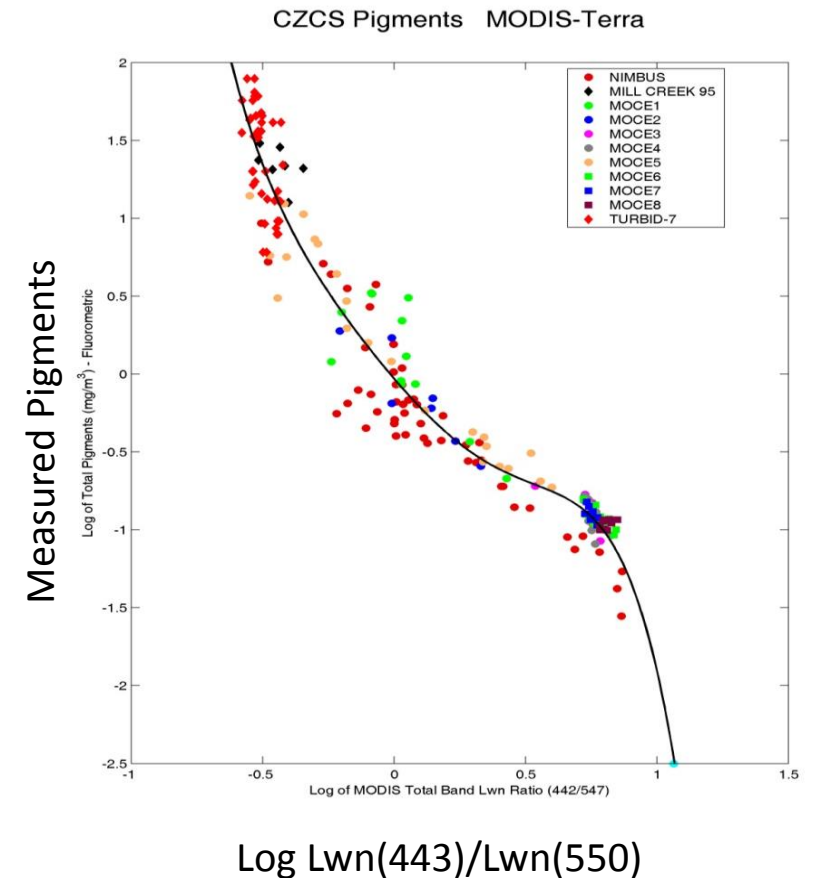
Pre- and Post deployment absolute calibrations
responsivity, wavelength, integration time, stray light

Validation data sets

Routine recalibration; operational monitoring; spot verifications
Internal LED and incandescent lamp sources
Diver-deployed reference lamps



Example Correction: Stray Light
Spectral biases such as this cause large biases in the chlorophyll product



Uncertainty in MOBY Products

Environmental

Instrument Self Shading (ISS)

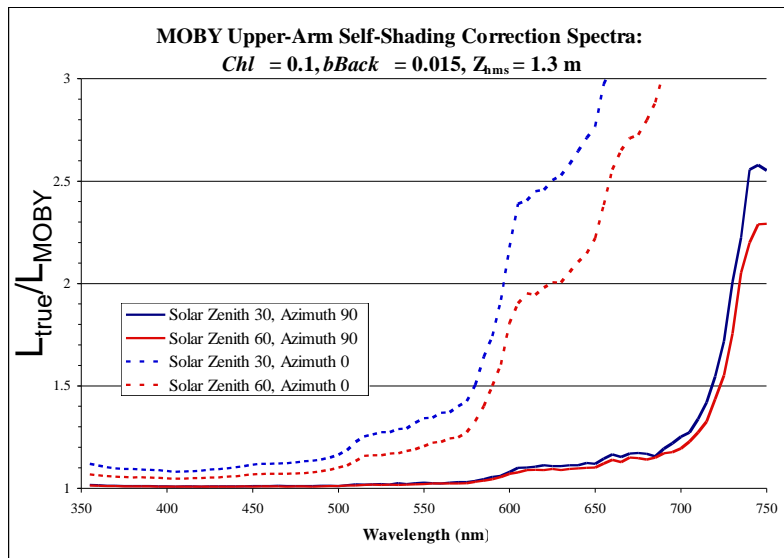
BRDF of water

Extrapolation of Lu at 1 m depth to just below the surface

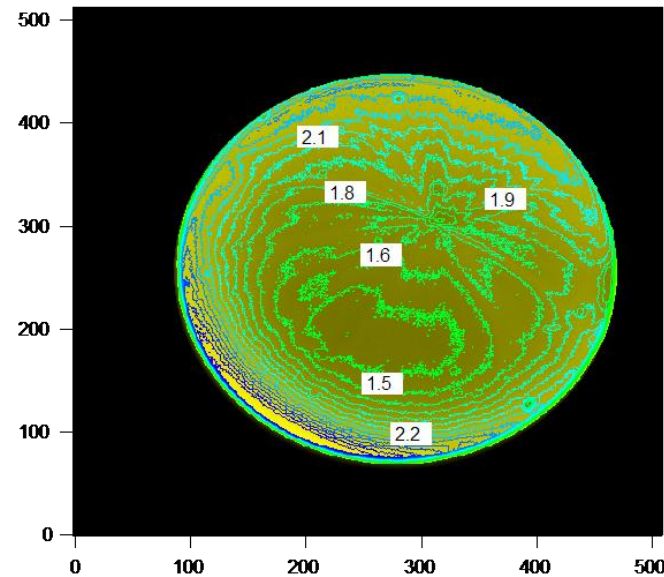
Cosine response of Es

Variability

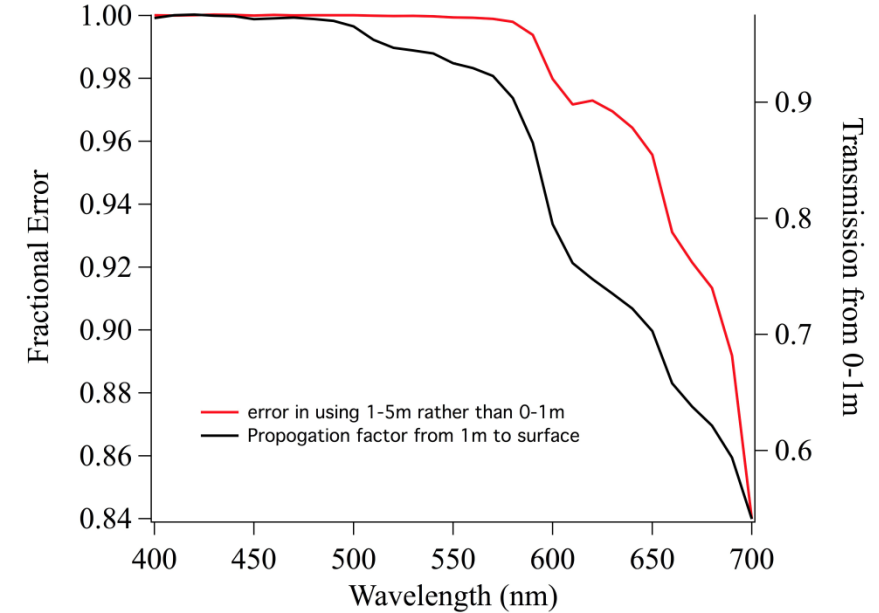
ISS introduces spectral biases as a function of buoy arm & sun position; optical properties



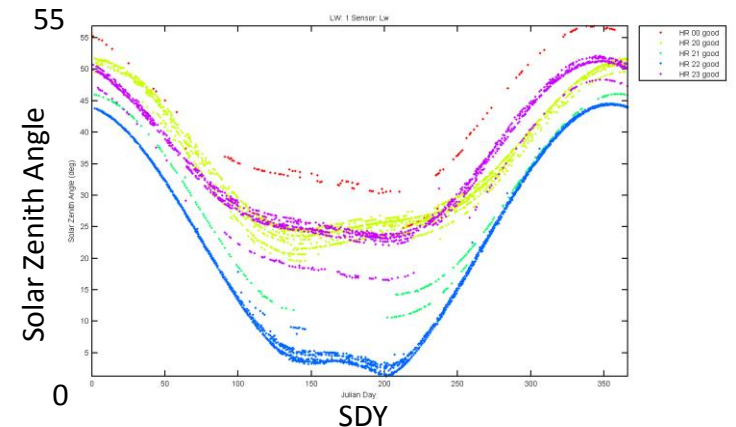
Upwelling radiance
distribution is not Lambertian



For $\lambda > 600\text{nm}$, KLu's from MOBY
fixed depths introduce spectral bias



Solar zenith angle varies, as
does diffuse/direct ratio



Ocean Color Validation

Aerosol Robotic Network – Ocean Color (AERONET-OC)

This work supports the VIIRS ocean color Earth Data Record (EDR) Team

NOAA

Menghua Wang

NRL

Bob Arnone

JRC

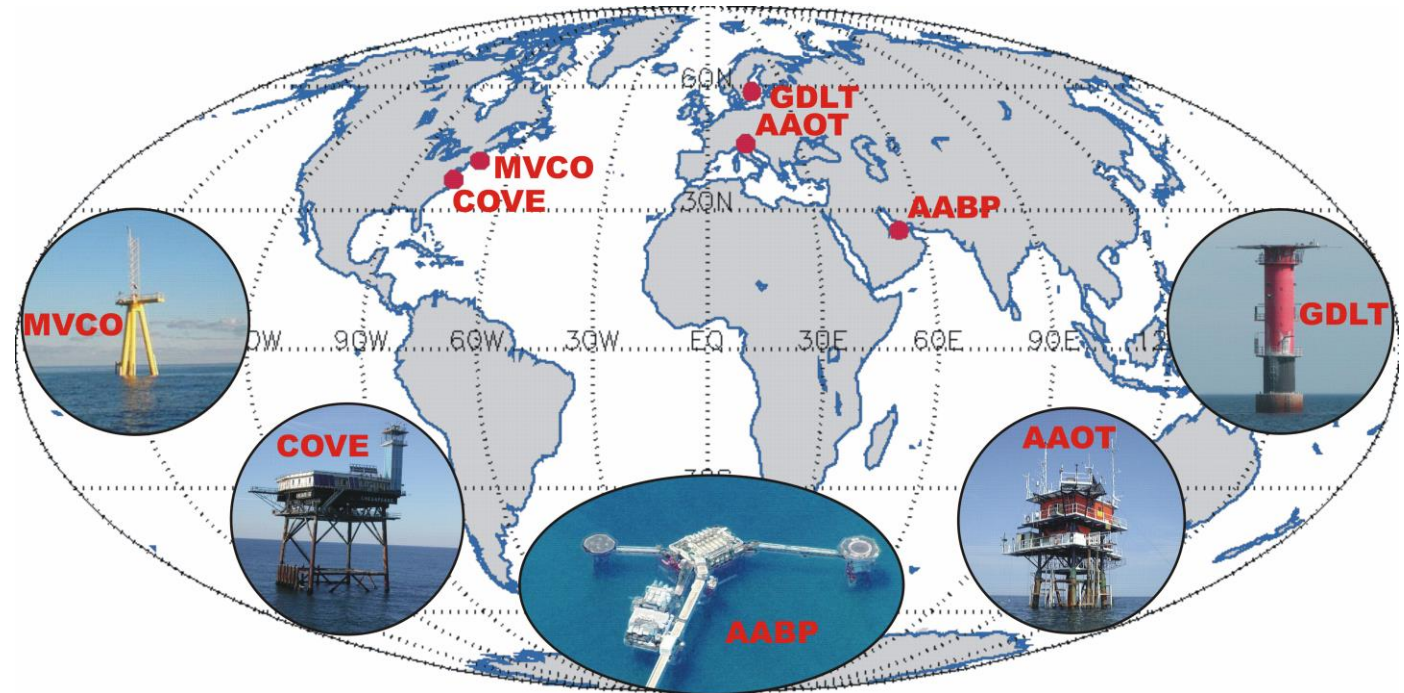
Giuseppe Zibordi

SDSU

Giulietta Fargion

NASA

Brent Holben



Credit: Giuseppe Zibordi

In Situ Validation from Satellite – AERONET-OC Matchups

Measure the sky radiance $L_i(\lambda, \theta', \phi)$ and the total radiance from the surface of the water $L_T(\lambda, \theta, \phi)$ at the specular zenith angle and same azimuthal angle; determine $L_w(\lambda, \theta, \phi)$ if reflectance $\rho(\lambda, \theta, \phi, \theta_0, W)$ is known. Here θ_0 is solar zenith angle and W is wind speed. Use platforms that provide unobstructed views of deep water without large biases from platform shadowing. Atmospheric correction uses the standard AERONET products.

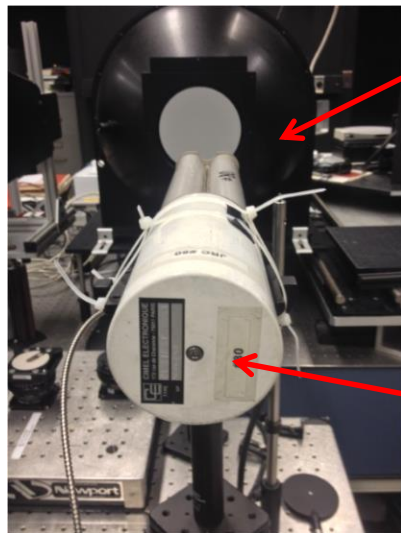
$$L_w(\lambda, \theta, \phi) = L_T(\lambda, \theta, \phi) - \rho(\lambda, \theta, \phi, \theta_0, W) L_i(\lambda, \theta', \phi)$$



Credit: Giuseppe Zibordi

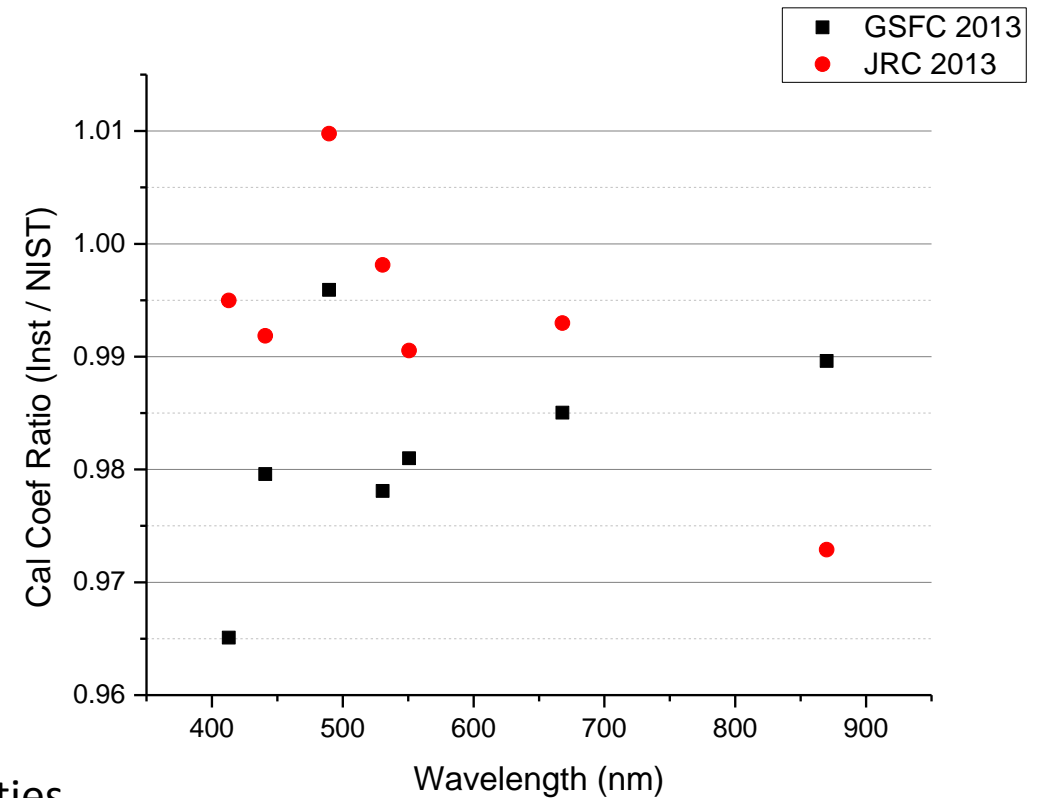
SeaPRISM080 Results

Characterize and calibrate a SeaPRISM for absolute radiance responsivity for several ocean color channels and compare to calibration coefficients from broadband sources (NASA/GSFC and JRC/Italy)



Laser-illuminated
sphere

SeaPRISM080



Developed hardware and software interface
Empirical model to explain anomalous behavior and nonlinearities
Validation using NIST reference sources

Summary

- Stable and long term collaborations have allowed NIST to make major impacts to ocean color *in situ* data sets
- Synergy among funding sources (internal vs external), area (specific measurement problems vs overall radiometric metrology), and usage (reference standard scales vs new technologies) has led to stronger programs and new capabilities